DEVELOPMENT AND RF EVAILJA"I'1ON O1' A FOUR-FREQUENCY SELECTIVE SURFACE SPACECRAFT SUBREFLECTOR ANTENNA

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ABSTRACT

NASA let Propulsion Laboratory has baselined a four frequency telecommunication system for the Cassini spacecraft antenna subsystems. 'l'his design required the design and development of a Frequency Selective Surface (FSS) subreflector that is integrated into the High Gain Antenna Subsystem. The FSS will be able to multiplex S, X, Ku, anti Ka frequency band wavelengths. 'l'he FSS design incorporates a periodic array of conducting elements on a Kevlar/Polymer composite structure. 'lie design requires the use of well characterized, low dielectric composite materials that are both mechanically and electrically stable over a broad temperature range and to be able to survive in a deep space environment. This paper will discuss the development, mechanical and RF electrical testing of two alternate designs as flat panel prototypes that were conducted to verify the multifrequency design approach.

INTRODUCTION

The Cassini project is a spacecraft being developed by JPL for interplanetary deep space exploration of Saturn. Cassini is a semi-autonomous spacecraft which will travel to Saturn, deploy a robotic probe to enter the planet's atmosphere, and then insert into orbit about planet. The Cassini project will use multiple RF frequencies at S (2.3 GHz), X (7.2 and 8.4 GHz), Ku (13.8 GHz), and Ka (32 and 34 GHz) bands for science investigations and data communication links. The telecommunication subsystem includes single high gain antenna (HGA) which incorporates a Frequency Selective Surface (FSS) subreflector to allow a cassegrain configuration at X and Ka bands, and a prime focus configuration at S and Ku bands. The use of FSS subreflector has a long tradition in spacecraft antennas [1,2], The use of FSS subreflectors are primarily used to enhance there multifrequency capabilities of antenna systems. they allow the use of non-collocating feeds at different frequencies, where the FSS subreflector possesses good reflecting characteristics at specified frequencies while being functionally "transparent" at others. The Voyager and Galileo spacecraft have FSS's which have dual screen cross-dipole patch elements which reflected X band and passed S bands. Other commercial and military spacecraft have made use of 3-frequency FSS subreflectors during the 1980's. What is unique with the Cassini program is the introduction of a four frequency multiplexing FSS subreflector for the }] GA. JPL during its system development phase began the development of analytical codes for the design of a four frequency FSS. The electrical RF design codes make use of multiple square or circular loop elements to optimize the RF performance at all four bands. For a more detailed discussion on Frequency Selective Surface and Grid Arrays, Reference 3 provides detailed information on FS S design, characterization and fabrication. This paper will discuss the development, preliminary mechanical analysis and RF electrical testing of two alternate designs as flat panels that were conducted to verify the multifrequency design approach early in the Cassini program. This work provided the baseline verification for the flight FSS system, The final flight antenna subsystem was fabricated by Alenia Spazio using a similar design approach.

To meet the Cassini antenna sub-system RF requirements, two design approaches were considered. Schematics of the two designs arc shown in Figure 1. The first design, referred to as the Add-on approach, was to use two FSS screens. The front FSS screen (Ka surface) reflects Ka band, but passes S, X, and Ku. The back screen (3 frequency surface) reflects X band, but passes S and Ku. The second design, referred to as the Integrated approach, uses only a single FSS screen to reflect X and Ka wavelengths, but pass S and Ku wavelengths. The general RF requirements that this task are li steal in Table 1. The design approach was to optimize performance at 8.425 GHz and 32 GHz, while meeting performance requirements at the other frequencies,

For the spacecraft antenna, the FSS screens would be supported by a dielectric composite structure. Across section view of the two designs is shown in Figure 2. A double square loop (DSL) design was used for the grid elements to meet the RF design goals. Typical etched copper double square loop grid elements are shown in Figure 3. The grid elements for the add-on design were Fabricated on 2 mil Kapton sheets by contact photolithography. For the integrated design, the FSS grid elements were supported and etched on a high dielectric constant material, Duroid 6010.5 from Rogers Corporation. The FSS RF design and performance is strongly dependent upon the dielectric properties of the structure which supports it. This was the primary motivation for evaluating the FSS grid screens on representative composite components.

Table 1: General RF Frequency Selective Surface Requirements

FREQUENCY (GHz)	1.0SS (dB)	POLARIZATION
2.295 ± 0.005	0.88 ± 0.2s	Linear
7.171 ± 0.025	0.70 ± 0.80	Circular
8.425 ± 0.025	0.20 ± 0.10	Circular
13.80 ± 0.05	0.45 ± 0.20	Linear
32.00 ± 0.10	0.20 ± 0.30	Circular
34.505.0.10	0.70 ± 0.30	Circular

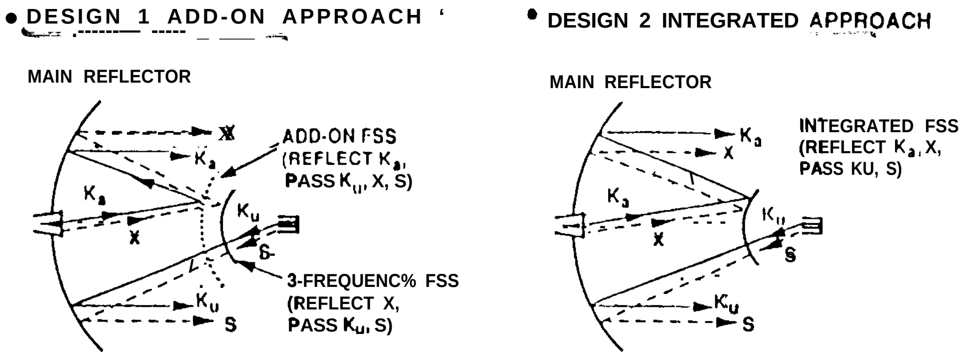

Figure 1. FSS Design Approaches

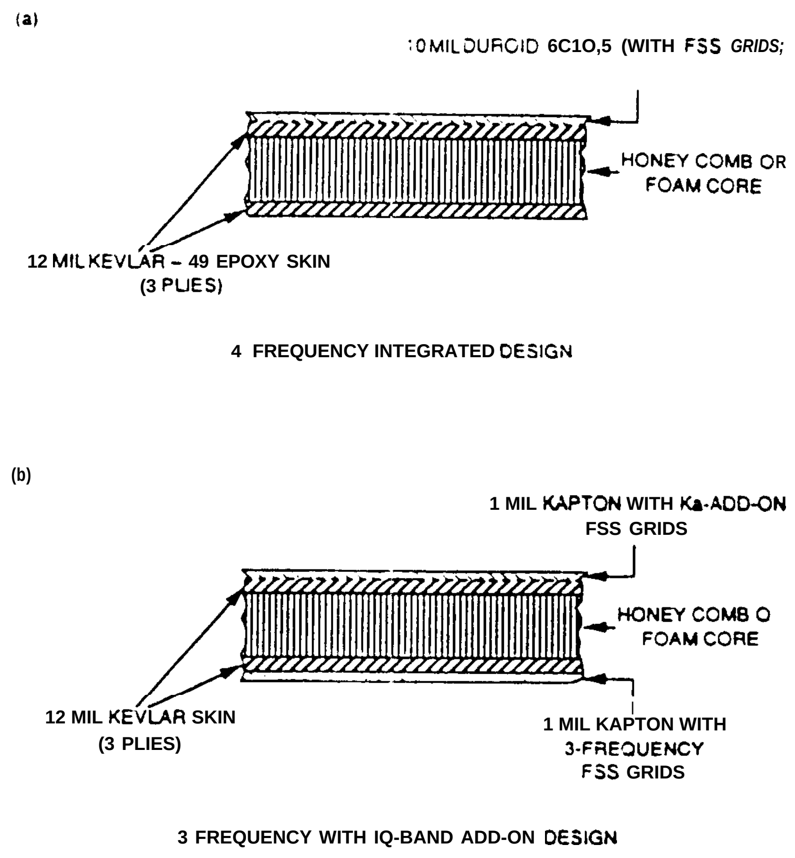

Figure 2. 1SS **Flat Panel Design Cross Sections**

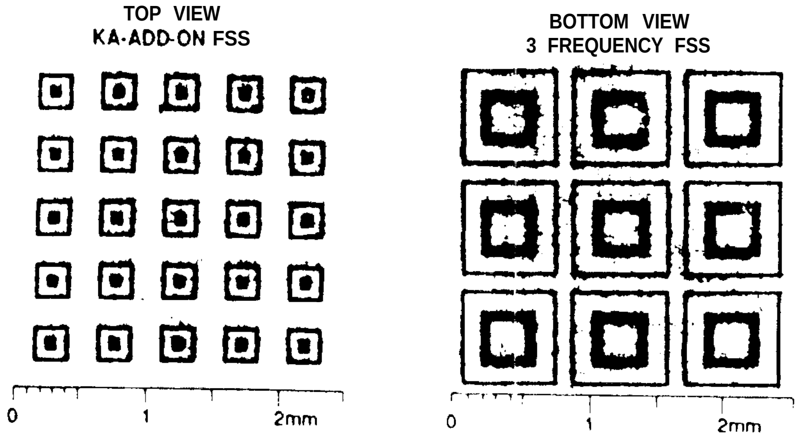

Figure 3. Representative double square loop FSS periodic array for the add-on design on Kevlar/Epoxy facesheet.

Materials and Mechanical Analysis

The primary performance criteria selecting materials for FSS structures is that they have a low dielectric loss, and that their dielectric properties would be frequency and temperature independent over the range of operation. The materials must be stable in the space environment, based on expected thermal and radiation exposure, and must not be a contamination source for the instruments on the spacecraft. The composite structure fabricated from the selected materials should be dimensionally stable, and have structural integrity through launch loads and mission lifetime. For the Cassini mission, the spacecraft's orbital trajectory will take it inward towards the Sun and will use Venus for a gravity assist. This orbital trajectory results in the heating of the entire antenna subsystem, At this time of this work there is uncertainty as to what the highest mission profile temperature which the FS S antenna must survive due to an incomplete thermal analysis and thermal control design. The work here will discuss an approach with a 398K (125"C) upper temperature limit design goal. Reference 4 presents a limited amount of work materials for a 473K (200 °C) design. The high temperature was a significant factor in the materials selection and mechanical development.

The electrical properties of the composite facesheets are determined by the constitutive electrical properties of the fiber and the resin. The fiber and the resin each have distinct electrical properties, but when they are fabricated as a composite, the resulting material has homogeneous electrical properties for the wavelengths considered here. Because of the complex microscopic behavior for the constitutive materials, there is no direct analytical approach to determine the dielectric constant or loss tangent. An approximate technique to estimate the dielectric constant is to use a rule of mixtures approach:

$$\varepsilon_{composite} = V_f\, E._f + V_r\, F._r + V_p\, \varepsilon_p$$

where V_r is the percent fiber by volume, V_f is the percent resin by volume, and VP is the percent porosity by volume, and ε_f, c,, and ε_p are the dielectric constants for the fibers, resin and porosity, respectively. 'l'he porosity is included in the determination of the electrical properties because even a small amount may affect the resonant frequency for FSS arrays. The porosity is typically air or vacuum and would have a dielectric constant of unity. There is no direct approach to estimate the loss factor for a composite material. For accurate modeling, both the dielectric constant and the loss tangent are best determined by measurement

The fibers provide the primary structural properties for the FSS in a composite structure. The fibers comprise 60% of a composite structure. The dielectric fibers which are currently in widespread use in composites are glass, quartz, Kevlar 49 and Spectra 1000. Glass and fused quartz are inorganic fibers, whereas the Kevlar 49 is an organic aramid fiber and the Spectra 1000 is an oriented high density linear polyethylene fiber. The glass fibers are available as either E glass or S glass. 'l'he glass fibers are currently available in developmental form as hollow fibers, with similar mechanical properties and an improvement in their electrical properties. Table 2 gives a summary of the fibers electrical properties of the fi hers. The glass fibers are the most common] y available fibers, and correspondingly the least expensive. The fused quartz has the lowest dielectric constant, but it is the most expensive. The hollow glass fibers have up to 30% hollow volume and are attractive for weight sensitive spacecraft applications. The Spectra fiber has the lowest density and a good combination of electrical and mechanical properties, but it is thermally unstable at temperatures above 130 'C. This would seriously limit its application for many uses.

I'able 2: Electrical properties at 20 °C and 10 GHz. of Common Dielectric Fibers alone and as composites (assumes 4090 epoxy resin)

	Fiber		Composite	
Fiber	Dielectric Constant	Loss Tangent	Dielectric Constant	10$s Tangent
S-2? Glass	5.21	.007	3.90	.014
E Glass	6.13	.004	4.70	.015
Fused Quartz	3.78	.0001	3.52	.017
Kevlar 49	3.55	.010	3.45	.015
Spectra 1000	2.30	.0004	2.42	.005
Hollow S-2 Glass	3.20	.005	3.20	.012
Hollow E Glass	3.95	.004	3.70	0.14

There are a wide range of polymeric resins which are used in dielectric applications, based on temperature range and structural requirements, For this study, a structural grade epoxy was used in the composite. It has a dielectric constant of 3.036 with a loss tangent of 0.010. It was chosen primarily due its history in spacecraft applications. There are other polymeric materials available for dielectric composites, such as cyanate-esters. A typical cyanate-ester polymer used in composites has a dielectric constant of 2.80 with a loss tangent of 0.001.

The mechanical properties of the fibers determine their use in dimensional stable applications. Table 3 gives the fiber longitudinal coefficient thermal expansion (CTE) properties, and the resulting thermal expansion for a quasi-isotropic composite. The CTE of quasi-isotropic composites presented are an analytical result that assumes a 60 % fiber volume with a polymer matrix of a typical epoxy. The results are based upon using the micromechanical modeling of composite laminates using the method of Chamis (4). As can be seen from Table 3, even though the quartz fibers have better electrical properties than the other fibers, it cannot produce the most dimensional stable composite laminate where the antenna is expected to see large temperature variations. It is for this reason that Kevlar has found an application on many spacecraft FSS that require dimensional stability due to thermal gradients on the structure. This becomes even more important at the application frequency increases, and the physical size of the FSS elements and their tolerance decreases. The required tolerance on the grid spacing dimensions is 0.0125 mm (0.5 roil). This tolerance is to be meet both during the fabrication of the grid screens and at the operation temperature, 73 K (-200 "C), of this antenna, Quartz and Ii-glass composites have found many applications on Earth orbiting satellite systems, where antenna temperatures are commonly near 20 °C.

l'able 3: Mechanical Properties of Composite Laminates Using Dielectric Fibers.

	Kevlar 49	E Glass	Quartz
Fiber CTE, Longitudinal (X 10-6 m/m °C)	-1.1	1.55	0.80
Fiber CTE, Transverse (X 10-6 m/m "C)	28.0	1.55	0.80
Resin CTE, bulk (X 10-6 m/m °C)	55	55	55
Quasi-isotropic Composite CTE	0,7	10.6	5.0

This task selected Kevlar 49 fiber for the laminate with epoxy as the resin. Two core materials were considered, a 0.25 inch cell Kevlar-epoxy honeycomb core, (Hexcel HRH-49), and Rohacell 51 -WF polymethacrylimide foam core. The film adhesives used were I/M-123-2, (.03 lb/ft^2 areal weight) with the honeycomb core, and Dupont Pyralux (1 mil thickness: was used with the Rohacell foam. All these materials have a flight history at JPL with the exception of the Pyralux film adhesive. Other core materials, such as Nomex cores were not evaluated because they could not meet the temperature requirements. "l'he maximum application temperature is near temperature limit of 150 'C for the Rohacell foam, but was considered because of its low dielectric constant (1.07) and because it is an isotropic material which simplifies the design and analysis of the off-angle RF performances.

A detailed mechanical analysis of the design concepts was completed to determine the in-plane and flexural moduli, thermal expansion characteristics and vibrational modes. Prom this the performance of the design concepts can be compared. The in-plane modulus of the designs were all near 0.6 GPa and the flexural modulus near 1.7 GPa. 'l'able 4 gives an estimate of the in-plane deflections due to a 370 K temperature change, the difference between the highest processing temperature and the coldest operating temperature. "l"he full scale antenna will have a 685 mm diameter. The core thickness was assumed to be 19.05 mm. Finite element analysis completed showed that the add-on design with composite core has better 3-dimensional stability over temperature extremes due to a more flexural balanced sandwich structure design and better core properties. The first dynamic mode for the add-on design with core was 66 Hz, compared to 59 Hz for the integrated design. The add-on approach is slightly stiffer because it is a more symmetric design.

Table 4. Estimated in-plane deflections due to 370 K temperature change from manufacturing to the operational temperature.

	Deflection Between Grids (mm)	Across 685 mm Surface mm	Through Core (mm)
Integrated with	0.0009	0.127	0.0036
-Kevlar Core			
- Rohacell Foam	0.0013	0.178	0.168
3 Frequency Add-on with	0.0012	0.168	0.0036
- Kevlar Core			
- Rohacell Foam	0.0016	0.2159	0.168

THEORETICAL BACKGROUND

The double square loop (DSL) FSS can be analyzed using the Equivalent Circuit Model (ECM) (6) , if the DSL patch array is etched on an electrically thin dielectric substrate (7). however, most of the FSS applications in space require that the FSS grids be imbedded between two dielectrics, and then supported by a dielectric composite structure. In genera], the FSS's characteristics are changed significantl y when the dielectric structure is added to the FS S grids. Namely, the dielectric materials tend to lower the FSS's resonant frequency and to stabilize its incident angle dependence (8). In addition, the RF losses in both the pass and stop bands are increased noticeably because the kevlar honeycomb structures have a relatively high loss tangent. For example, the Kevlar/epoxy facesheets used in this study has a loss tangent of 0.0156 at X band frequencies, while the Kapton film has a loss tangent of 0,0028.

The ECM can not accurately model the above mentioned effects caused by the dielectrics. Thus the accurate Integral Equat ion Formulation (IEF) solved by either the method of moments (9-12) or the Conjugate Gradient Method (CGM) (9) should be implemented for this particular application. Since these modeling techniques have been documented extensively in the literature (9,1 O), interested readers should look to those references for detailed equations and analysis. in general, the ECM approach uses simple algebraic formulations, hence it is a very efficient design tool. Once the first order FSS grid design is obtained by the ECM approach, the sophisticated IEF approach should be implemented to get more accurate results and to account for the dielectric effects.

To accurately model the two screen FSS with different lattice geometry is a very difficult task (10). The simplified cascading approach of considering only one lattice interaction mode has been investigated previously (13- 15) to give a reasonably accurate results for electrically large screen separation. For small separations one needs to include not only the fundamental mode, but also the higher order interaction modes (10). In fact, it was found that for screen separations greater than 0.5 inch, the single mode approximate ion should give accurate results for the Cassini FS S. Since the Add-on design has a 0.S inch, the single mode approximation is employed to predict the two screen FSS performance.

RF TESTING AND EVALUATION

RF tasks included the RF design and testing the transmission characteristics and reflection patterns of the flat panel FSS's. The goal of this task was to accurately determine the materials dielectric properties, and to design and develop hardware and software capabilities for a four-frequency FSS. RF tests were performed at room temperature of a series of 20 inch by 20 inch flat panels in an anechoic chamber. A schematic of the FSS transmission measurement system is shown in Figure 4. The setup uses standard gain horns as the transmitting and receiving antennas. By turning the horn antenna polarization from vertical to horizontal, one can measure both Transverse Electric (TE) and Transverse Magnetic (TM) polarizations. By rotating the flat panel about the center axis, the performance at incident angles up to 45° could be evaluated.

'l'he add-on design and the integrated design were both tested with the Kevlar-epoxy honeycomb *core* and with the Rohacell foam, at core thicknesses of 12.7 mm, 19 mm and 25.4

mm. the testing was completed in two stages. The first step was to use the validated FSS screens to experimentally determine the dielectric constant of the Kevlar-epoxy/core sandwich structure. "l"he next step was to validate the RF design performance of the individual FSS screens. In all cases the effective dielectric constant for the sandwich structure was less than what was assumed for the constituent materials using a rule of mixtures approach. The effective change in the dielectric constant appeared experimentally as a resonant frequency shift. This necessitated a redesign of the FSS screens to match the dielectric properties of the composite structure and to meet RF requirements.

Because of the volume of test results are extensive, only a representative portion will be presented here. Complete results are available in Reference 4. The first result was that testing each design at three thickness showed that there was no interaction effects with a screen separation greater than 12.7 mm, The second result was that no noticeable performance difference was found between the use of the honeycomb core or the Rohacell foam, with equivalent Kevlar/epoxy facesheets. Figure 5 shows typical test results for the add-on design at normal incidence. There was excellent agreement between the computed and the experimental results. Figure 6 shows a comparison between the computed and measured performance of the 4-frequency integrated FSS at normal incidence. Tables 5 and 6 give a summary of the test results for the add-on design and the integrated dcsi gn. The results give both dB loss at test inclinations of 0°, 30°, and 45° angles. Note that the losses at 2.3 and 13.8 GHz are transmission losses, while the losses at 7.2, 8.4, 32 and 34 GHz are reflection losses the FSS grid elements were designed to optimize RF performance at X and Ka bands.

Table 5: RF loss summary for the add-on design with honeycomb core

	Loss (dB)				
Frequency	0°	30°		45°	
(GHz)		TE	TM	TE	TM
2.3	0.41	0.50	0.33	0.68	0.23
7.2	0.65	0.73	1.10	0.85	1.95
8.4	0.14	0.17	0.19	0.22	0.29
13.8	1.10	1.20	0.73	2.10	0.53
32.0	0.53	0.19	0.22	0.21	0.48
34.()	0.21	0.28	0.33	0.20	0.30

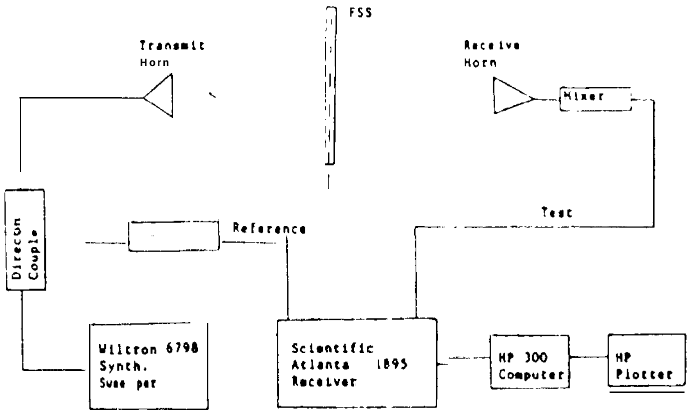

Figure 4. FSS transmission measurement set-up

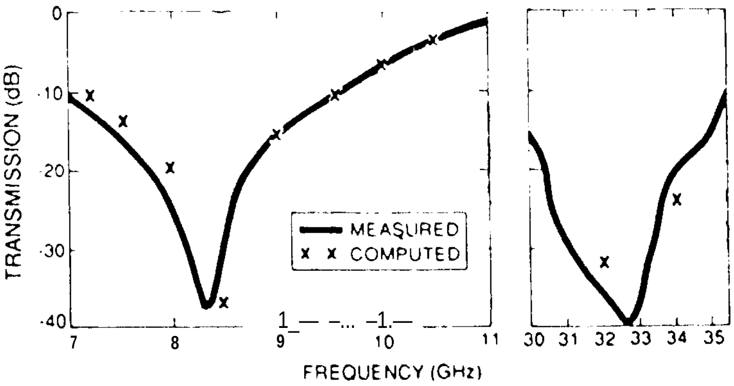

Figure 5. Comparison between the measured and computed RF transmission test results for the Add-on design

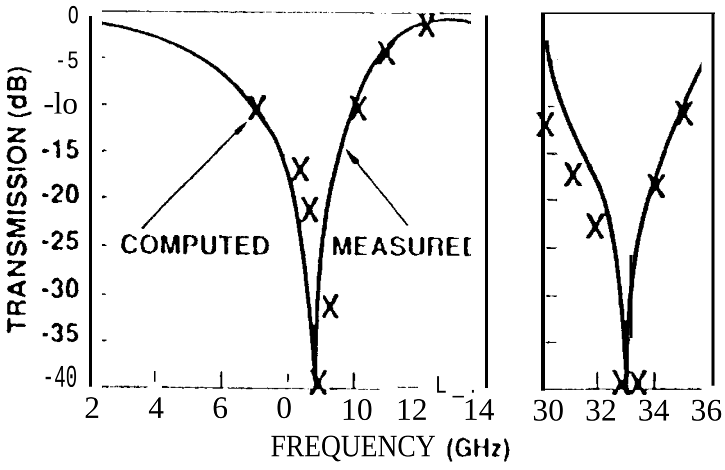

Figure 6. {Comparison between the measured and computed RF transmission test results for the Integrated design

Table 6: RF loss summary for the Integrated design with honeycomb core

Frequency (GHz)	Loss (dB) 0°	30° TE	30° TM	45° TE	45° TM
2.3	0.95	1.20	0,73	1.60	0.50
7.2	0.45	0.37	0.61	0.27	0.90
8.4	0.08	0.07	0.11	0.06	0.16
13.8	0.37	0.56	0.29	0.90	0.20
32,0	0,09	0.17	0.13	0.16	0.69
34.0	0.14	0.20	0.21	0.13	0.43

5. Summary

Two design approaches and a criteria for. selecting materials have been presented for the development of a four-frequency FSS spacecraft antenna. There is a direct interaction between the dielectric "properties of "the structure and the frequency selective surface. The choice of materials has to be tailored to the application environment, and then the grid design is optimized to the structures electrical properties. The integrated and acid-on design approaches were evaluated as flat panels and compared to theoretical predictions. The integrated approach provided better RF performance than the add-on design. The add-on design had slightly better mechanical properties.

6. References

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7. ACKNOWLEDGMENTS

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

8. BIOGRAPHY

Gregory Hickey received a B.S. from U.C. Berkeley and M.S. from the University of Virginia, both in Chemical Engineering. He has been at JPL for the last 9 years in The Mechanical Systems Division. His primary work has been in the development and characterization composites structures for space applications, including antenna structures and planetary rovers. He has published over 30 papers in journals and at conferences regarding advanced materials, has two patents, and co-authored a book on Frequency Selective Antennas and Grid Arrays.

Te-Kao Wu received a B. S. degree from National Taiwan University and M.S. and Ph.D. in Electrical Engineering from the University of Mississippi. He has been at TRW Antenna Systems Department. for the last 2 years. Prior to this he was at JPL for 5 years in the Spacecraft Telecommunications Section, after 7 years at Hughes Antenna Systems Laboratory, El Segundo, CA. He has over 30 publications in the areas of FSS, antennas, electromagnetic and measurement techniques. He edited and co-authored a book on Frequency Selective Antennas and Grid Arrays.